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BULK ACOUSTIC WAVE RESONATOR AND CIRCUIT COMPRISING SAME

TECHNICAL FIELD

This patent application describes a resonator operating with bulk acoustic waves (or FBAR, Thin Film Bulk Acoustic Wave Resonator), also known as BAW resonator (Bulk Acoustic Wave Resonator), as well as a circuit constructed of such resonators.

BACKGROUND

BAW resonators are suitable, in particular, for band-pass high-frequency filters in modern filter technology, and can be used, for example, in mobile communication devices.

A resonator operating with bulk acoustic waves has a piezoelectric layer that is disposed between two metal layers (electrodes). A sequence of layers can also be used instead of only one piezoelectric layer. The layers are deposited consecutively on a substrate and structured into resonators, which are electrically connected to one another and together can constitute a filter circuit, for example, especially a band-pass filter. Such a band-pass filter can also be used together with another filter in a duplexer.

Figure 1 shows the equivalent circuit diagram of a BAW resonator. Outside a frequency range surrounding the resonant frequency, the resonator is characterized by a static capacitor C_0 and, in proximity to the resonant frequency, by the connection in series

of a resistor R_m, a capacitor C_m and an inductive resistor L_m. The static capacitor is essentially defined by the resonator surface area and the thickness of the piezoelectric layer. The resistor R_m describes losses in the resonator, while the capacitor C_m and the inductive resistor L_m determine the resonant frequency $f_r = \frac{1}{2\pi\sqrt{L_m C_m}}$. The ratio C_m/C_0 determines the coupling of the resonator. The coupling coefficient k of the resonator is linked to the resonant frequency f_r and the antiresonant frequency f_a: $k^2 = \frac{f_a^2 - f_r^2}{f_a^2}$, wherein $f_a = f_r \sqrt{1 + C_m/C_0}$.

A band-pass filter is characterized by a transfer function that has, in particular, a transmission band and several stop bands. The transmission band is, in turn, characterized by its bandwidth, the insertion attenuation in the transmission band and the edge steepness at the edge of the transmission band.

Two BAW resonators SR1 and SR2 (as depicted schematically in Figure 2) can be acoustically coupled with one another if, for example, they are arranged in a stack on top of one another. In this connection, the resonators form a series connection between a port P1 and a port P2, e.g., in a stacked-crystal arrangement, in which two resonators share a common electrode, which is connected to ground (see Figure 3), or are arranged in a coupled-resonator arrangement, in which a coupling layer KS is arranged between the upper electrode E2 of the lower resonator and the lower electrode E3 of the upper

resonator, and said electrodes are connected to ground (see Figure 4). A first resonator in Figure 3 comprises a piezoelectric layer PS1, which is arranged between two electrodes E1 and E2, and an acoustic mirror AS arranged below the electrode E1, said acoustic mirror resting on a carrier substrate TS. Above the first resonator, a second resonator is arranged that comprises a piezoelectric layer PS2, which is arranged between the electrode E2 and an electrode E3. Electrode E1 is connected to port P1, electrode E3 to port P2 and electrode E2 to ground.

The layer system shown in Figure 4 includes a first resonator arranged on a carrier substrate TS, a coupling layer KS disposed above it and a second resonator arranged above the coupling layer KS. The first resonator is arranged as described in Figure 3, and is connected between port P1 and ground. The second resonator contains (from bottom to top) two electrodes E3 and E4 and a piezoelectric layer PS2 arranged between said electrodes, the second resonator being connected between port P2 and ground. The coupling layer KS arranged between said resonators provides for acoustic coupling between these resonators.

Filters constructed of acoustically coupled resonators are characterized by a high stop band suppression. However, the edge steepness and, with it, the adjacent channel selectivity are comparatively low, due to the absence of defined pole positions in proximity to the pass band.

BAW resonators can be connected in a ladder-type or a lattice-type construction. The advantage of the lattice-type arrangement of the resonators in a band-pass filter is that the selection of such a filter in stop band areas well outside the transmission band is very good, ranging, for example, between -40 and -60 dB. The disadvantage of this filter arrangement includes a low edge steepness of the transmission band. For this reason, it may be difficult, in this type of filter arrangement, to achieve sufficient attenuation of the signal in the stop band in proximity to the transmission band.

Considerable edge steepness is required in some applications. In the case of duplexers that are suitable for the PCS telecommunications standard, for example, a decline in the transmission function from ca. -3 dB to significantly below -40 dB within a frequency range of only 20 MHz must be guaranteed. Previously known band-pass filters, which are constructed of BAW resonators, may not satisfy such requirements, due to additional frequency shifts in the edges in response to temperature change or as a result of existing production tolerances (which, in the case of a filter operating at ca. 2 GHz and having BAW resonators that contain a piezoelectric layer of ALN, can amount to several MHz).

It is known, from the reference EP 0949756 A2, that a series connection of stacked resonators acoustically coupled with one another, as well as additional resonators instead of only one resonator in a filter circuit, improves edge steepness in the transmission band

of the filter. The disadvantage of this solution, however, is that it requires a great deal of space.

SUMMARY

This patent application describes a resonator operating with bulk acoustic waves (also known as BAW resonator - Bulk Acoustic Wave Resonator - or FBAR - Thin Film Bulk Acoustic Wave Resonator), which is constructed of a sequence of layers containing the following layers: a first layer region that comprises a first electrode, an upper layer region that comprises a second electrode and, between the two, a piezoelectric layer. A capacitor is connected in parallel or in series to the resonator.

The connection in parallel of a BAW resonator and a capacitor C_a instead of a non-connected resonator reduces the effective coupling of the BAW resonator (that is, the distance between the resonant and antiresonant frequency of the resonator), in that the effective static capacitor C'_0 is increased, $C'_0 = C_0 + C_0$. In this connection, the resonant frequency f'_r of the new circuit (series resonance, or the resonant frequency of the serial resonant circuit formed by C_m, L_m and R_m) remains unchanged relative to the resonant frequency f_r of the (non-connected) resonator, $f'_r = f_r$. In contrast, the antiresonant frequency $f'_a = f_r\sqrt{1 + C_m / C'_0}$ (parallel resonance, or the resonant frequency of the parallel resonant circuit formed by C'_0, C_m, L_m and R_m) is lower than the antiresonant frequency

$f_a = f_r\sqrt{1+C_m/C_0}$ (parallel resonance, or the resonant frequency of the parallel resonant circuit formed by C_0, C_m, L_m and R_m) of the (non-connected) resonator. As a result, the edge steepness of a band-pass filter comprising such BAW resonators is increased.

The connection in series of a BAW resonator and a capacitor C_a instead of a non-connected resonator reduces the effective coupling of a BAW resonator (that is, the distance between the resonant and the antiresonant frequency of the resonator). In the connection, the antiresonant frequency f'_a of the circuit (parallel resonance, or the resonant frequency of the parallel resonant circuit formed by C_0, C_m, L_m and R_m) remains unchanged relative to the antiresonant frequency f_a of the resonator, $f'_a = f_a$. In contrast, the resonant frequency $f'_r = f_r\sqrt{1+C_m/(C_a+C_0)}$ (series resonance, or the resonant frequency of the serial resonant circuit formed by C_0, C_m, L_m and R_m) of the circuit is higher than the resonant frequency f_r (series resonance, or the resonant frequency of the serial resonant circuit formed by C_m, L_m and R_m) of the resonator. As a result, the edge steepness of a band-pass filter comprising such BAW resonators is increased.

In an embodiment, the resonator is arranged on a carrier substrate. It is also possible to arrange the resonator over an air gap provided in the carrier substrate.

The first and the second electrode may include an electrically conductive material, such as a metal or a metal alloy.

The piezoelectric layer may include AlN, but can include another material with piezoelectric properties (such as ZnO). It is also possible that the piezoelectric layer comprises a plurality of adjacent or separated, identical or different layers with piezoelectric properties.

It is possible that the first and/or the second electrode has a multilayer structure comprised of two or more adjacent layers of different materials. It is also possible that the piezoelectric layer in the resonator comprises two or more adjacent or separated layers of different materials.

It is possible that, additionally, a layer resistant to dielectric discharge is arranged between the first and the second electrode, where the layer protects the resonator against electric arcing between the electrodes.

The connection of a capacitor in parallel to a BAW resonator can be accomplished in a filter constructed, for example, in a ladder-type construction, in a lattice-type construction or as an SCF (Stacked Crystal Filter), as well as of any combination of BAW resonators.

It is possible to provide for the connection of a capacitor in parallel to a BAW resonator in only one serial branch or in a plurality of serial branches of a filter. It is also

possible to provide for the connection of a capacitor in parallel to a BAW resonator in only one parallel branch or a plurality of parallel branches of a filter. In a further embodiment, it is possible that the connection of a capacitor in parallel to a BAW resonator be provided in at least one serial branch or in at least one parallel branch of the filter.

In embodiments, the value of the capacitor connected in parallel to a BAW resonator may be between 0.1 and 10 pF.

It is advantageous when the coupling of the resonator is reduced only in the serial branches or only in the parallel branches of a filter or a duplexer by the connection in parallel of the corresponding capacitors.

It is possible to implement the capacitor connected in parallel to a BAW resonator by connecting a discrete capacitor in parallel to the BAW resonator. Another possibility is to realize such a capacitor in the carrier substrate by structured metal layers. It is also possible to arrange an additional dielectric layer between the electrodes of the BAW resonator to increase the capacitance of the BAW resonator. This dielectric layer can be arranged between the piezoelectric layer and one of the electrodes or between two piezoelectric layers.

The parasitic capacitance of the respective resonator can also be deliberately selected to be as large as possible, for example by enlarging the electrode surface to improve the edge steepness of the filter constructed of such resonators. Other implementations not cited here are also possible.

It is possible that the lower and/or upper layer region of the resonator may include one or more layers. It is also possible that an acoustic mirror is realized in the lower and/or in the upper layer region, where the mirror comprises at least two alternating layers having different acoustic impedance.

The acoustic mirror may comprise alternating layers, each having a high and a low acoustic impedance, each of their layer thicknesses comprising approximately a quarter wavelength of the acoustic main mode (relative to the velocity of expansion of the acoustic wave in the respective material). The acoustic mirror thus provides one and/or a plurality of boundary surfaces, which, at the resonant frequency of the acoustic wave, reflect back into the resonator and prevent the wave from escaping in the direction of the carrier substrate.

In a further advantageous embodiment, one of the layers of the acoustic mirror can simultaneously constitute one of said electrodes.

The use of a BAW resonator with a capacitor connected in parallel in the circuit of a band-pass filter increases the edge steepness of the transmission band of the band-pass filter. As a result, the attenuation of the signal is increased in the stop bands in proximity to the transmission band. This is advantageous in the case of realization of a duplexer circuit having such a band-pass filter.

Another embodiment includes an electric circuit containing a resonator stack that comprises at least two resonators arranged on top of one another and operating with bulk acoustic waves and at least one additional resonator or resonator stack having BAW resonators. Each of the resonators operating with bulk acoustic waves comprises a lower electrode, an upper electrode and a piezoelectric layer arranged between the two. In this connection, the resonators arranged on top of one another in the resonator stack form a serial connection, e.g., in a stacked crystal arrangement (when both resonators have a shared electrode) or a coupled resonator arrangement (when a coupling layer is provided between the upper electrode of the lower resonator and the lower electrode of the upper resonator).

In this connection, the upper electrode of the lower resonator operating with bulk acoustic waves and the lower electrode of the upper resonator operating with bulk acoustic waves, which are arranged in the resonator stack, is electrically connected with one of the electrodes of at least one additional resonator or resonator stack.

The connection can be viewed as a basic element of a ladder-type arrangement or (in the case of a suitable connection) of a lattice-type arrangement of individual resonators, at least two of the resonators being acoustically coupled with one another and arranged on top of one another. In this connection, it is possible that two BAW resonators arranged on top of one another in a stack realize two serial resonators or parallel resonators of the ladder-type arrangement or of the lattice-type arrangement. It is also possible that two BAW resonators arranged on top of one another in a stack realize one serial resonator and one parallel resonator of the ladder-type arrangement or the lattice-type arrangement.

A coupling layer may be provided between the upper electrode of the lower resonator operating with bulk acoustic waves and the lower electrode of the upper resonator operating with bulk acoustic waves, which are arranged in the resonator stack.

The at least one additional resonator can, for example, be a resonator with bulk acoustic waves, a resonator operating with acoustic surface waves, an LC resonator or a resonator stack as specified above.

The second electrode of the at least one additional resonator, which is not connected to the resonators arranged on top of one another in the resonator stack, can be connected to ground or to a subsequent resonator and/or to a resonator stack not yet specified.

The circuit represents an advantageous combination of different filter arrangements, such as the arrangement of the resonators stacked on top of one another and acoustically coupled with one another, as well as a ladder-type arrangement and/or a lattice-type arrangement. The transfer function of a filter whose basic elements realize the circuit, as compared with the transfer function of a filter constructed of resonator stacks known in the art, exhibits significantly steeper edges in the transmission band of the filter. This results in good adjacent channel selectivity of the filter.

The circuit that includes a resonator stack and a resonator electrically connected with it as specified above may comprise a basic element of a filter.

It is possible that a plurality of parallel resonators, each of which is arranged in a parallel branch of different basic element electrically connected with one another, are acoustically connected with one another and/or arranged on top of one another. It is also possible that, instead of only one resonator being realized in the parallel branch (parallel resonator) of a basic element of the circuit, two (e.g., coupled with one another) parallel resonators connected in series or in parallel are realized.

It is also possible that more than only two serial resonators are arranged on top of one another and/or acoustically coupled with one another.

The basic elements of the described above can be combined with one another in any manner.

In the following, embodiments are explained in greater detail on the basis of figures that are schematic and, therefore, not true to scale.

DESCRIPTION OF THE DRAWINGS

Figure 1 shows an equivalent circuit diagram of a BAW resonator.

Figure 2 shows the circuit diagram of a resonator stack.

Figure 3 shows a resonator stack with acoustically coupled BAW resonators in schematic cross-section (state of the art) .

Figure 4 shows another example of a resonator stack with acoustically coupled BAW resonators and a coupling layer in schematic cross-section (state of the art) .

Figure 5a shows an equivalent circuit diagram of a BAW resonator with a capacitor connected in parallel.

Figure 5b shows an equivalent circuit diagram of a BAW resonator with a capacitor connected in series.

Figure 6a shows a basic element of a filter realized in ladder-type construction with a capacitor connected in parallel to a BAW resonator in the serial branch.

Figure 6b shows the transfer function of a filter realized in ladder-type construction without and with a capacitor connected in parallel to a BAW resonator in the serial branch.

Figure 7 shows a basic element of a filter realized in ladder-type construction with a capacitor connected in parallel to a BAW resonator in the parallel branch.

Figure 8a shows an exemplary embodiment of a filter realized in ladder-type construction with capacitors connected in parallel to BAW resonators in the serial branches.

Figure 8b shows the transfer function of a filter realized in lattice-type construction without and with a capacitor connected in parallel to a BAW resonator in the serial branch.

Figure 9 shows an exemplary embodiment of a filter realized in lattice-type construction with capacitors connected in parallel to BAW resonators in the parallel branches.

Figure 10 shows a connection of a resonator stack in the serial branch and of an additional BAW resonator in the parallel branch, in circuit diagram (a) and in schematic cross-section (b), respectively.

Figure 11 shows an advantageous exemplary embodiment of a connection of a resonator stack and of an additional BAW resonator in schematic cross-section.

Figure 12 shows a connection of a resonator stack in the serial branch and of an additional resonator stack in the parallel branch, in circuit diagram (a) and in schematic cross-section (b), respectively.

DETAILED DESCRIPTION

Figures 1 to 4 have already been discussed earlier. Figure 5a shows an equivalent circuit diagram of a BAW resonator with a capacitor C_a connected in parallel to it. Outside the resonant frequency range, the resonator includes a static capacitor C_0 and, in proximity to the resonant frequency, by a resistor R_m, a capacitor C_m and an inductive resistor L_m. The resistor R_m describes losses in the resonator, while the capacitor C_m and the inductive resistor L_m determine the resonant frequency. The ratio C_m/C_0 determines the coupling of the resonator. The addition of a capacitor C_a connected in parallel to the resonator results in reduction of the effective coupling of the resonator, which is now determined by $C_m/(C_0 + C_a)$, instead of C_m/C_0.

Figure 5b shows an equivalent circuit diagram of a BAW resonator with a capacitor C_s connected in series to it.

An exemplary connection of two BAW resonators RA and RB in ladder-type construction and a capacitor C_a connected in parallel to one of the resonators is shown in Figure 6a. Resonator RA is arranged in a serial branch and resonator RB in a parallel branch of the circuit. Two resonators connected in this manner represent, for example, a basic element of a ladder-type filter known in the art.

In Figure 6a, the capacitor C_a is integrated in the serial branch of the circuit. In this connection, it is connected in parallel to the serial resonator RA, as a result of which

the steepness of the right edge of the transfer function in the transmission band can be controlled and/or increased. Such a basic element can, for example, be used in a transmission filter (Tx filter) of a duplexer, especially a PCS duplexer.

Figure 6b shows the transfer function S21 of a filter realized in ladder-type construction without and with a capacitor connected in parallel to a BAW resonator in the serial branch. The transfer function of the filter constructed of BAW resonators in the ladder-type construction known in the art is indicated by a dashed line 11. The transfer function of the filter in ladder-type construction with a capacitor connected in parallel to a BAW resonator in the serial branch is indicated by a continuous line 12, wherein the transfer function, in this case, has a steeper right edge of the transmission band.

In Figure 7, the capacitor C_a is integrated in the parallel branch of the circuit. In this connection, it is connected in parallel to the parallel resonator RB, as a result of which the steepness of the left edge of the transfer function in the transmission band can be controlled and/or increased. Such a basic element can, for example, be used in a reception filter (Rx filter) of a duplexer, especially a PCS duplexer.

The capacitor C_a can be arranged on a carrier substrate, together with the BAW resonator. The capacitor C_a can also constitute a discrete component with external electrodes, which is electrically connected with the BAW resonator as described above.

It is also possible that the capacitor C_a is realized in the metallized layers of the (multilayer) carrier substrate and, as described above, is electrically connected with the BAW resonator by, for example, feedthroughs, bump connectors or bond wires.

An example of a connection of two BAW resonators RA and RB in lattice-type construction and a capacitor C_a connected in parallel to one of said resonators is shown in Figure 8a. A resonator RA is arranged in a serial branch, and a resonator RB in a parallel branch of the circuit. Figure 8a shows two pairs of resonators connected in this manner, which, for example, constitute a basic element of a filter realized in lattice-type construction.

In Figure 8a, each of two capacitors C_a is integrated in a serial branch of the circuit. In this connection, each is connected in parallel to the corresponding serial resonator RA, as a result of which the steepness of the right edge of the transfer function in the transmission band can be controlled and/or increased. Such a basic element can, for example, be used in a transmission filter (Tx filter) of a duplexer, especially a PCS duplexer.

Figure 8b shows the transfer function S21 of a filter realized in lattice-type construction without and with a capacitor connected in parallel to a BAW resonator in the serial branch. The transfer function of the filter constructed of BAW resonators in the lattice-type construction known in the art is indicated by a dashed line 11. The transfer

function of the filter in lattice-type construction with a capacitor connected in parallel to a BAW resonator in the serial branch is indicated by a continuous line 12, wherein the transfer function, in this case, has a steeper right edge of the transmission band.

In Figure 9, each of two capacitors C_a is integrated in a parallel branch of the circuit. In this connection, each is connected in parallel to the parallel resonator RB, as a result of which the steepness of the left edge of the transfer function in the transmission band can be controlled and/or increased. Such a basic element can, for example, be used in a reception filter (Rx filter) of a duplexer, especially a PCS duplexer.

Figure 10a shows the circuit diagram of a connection of a resonator stack, which comprises the BAW resonators SR1 and SR2, in the serial branch, and of an additional BAW resonator PR in the parallel branch. The resonator stack is connected between ports P1 and P2. An exemplary realization of such a circuit is shown in schematic cross-section in Figure 10b. The resonator stack comprises the piezoelectric layer PS2, which is arranged between two electrodes E1 and E2 (center electrode). The piezoelectric layer PS2 is arranged above them. An electrode E4 connected to the port 2 lies on the piezoelectric layer PS2. The port P1 is electrically connected with the electrode E1. The layer sequence E1, PS1 and E2 realizes, for example, the resonator SR1 in accordance with Figure 10a. The layer sequence E2, PS2 and E4 realizes, for example, the resonator SR2 in accordance with Figure 10a. Here, the resonator PR in the parallel branch of the circuit according to Figure 10a is realized by the layer sequence E6 (electrode), PS3

(piezoelectric layer) and E5 (electrode), the electrode E5 being electrically connected with the center electrode E2. In this exemplary embodiment, the electrode E6 is connected to ground. It is also possible that it be connected to another circuit not shown here.

Figure 11 shows, in schematic cross-section, an embodiment of a resonator stack and an additional BAW resonator. The resonator stack includes, from bottom to top, a first electrode E1, a first piezoelectric layer PS1, a second electrode E2, a coupling layer KS1, a third electrode E3, a second piezoelectric layer PS2 and a fourth electrode E4. The resonator stack forms two resonators arranged on top of one another and coupled with one another by the coupling layer (corresponding to SR1 and SR2 in Figure 10a), and is connected between ports P1 and P2. The parallel branch of the circuit is formed by an additional resonator, which includes a third piezoelectric layer PS3 and electrodes E5 and E6 surrounding it. Electrodes E2 and E3 are connected with electrode E5. Here, electrode E6 is connected to ground. It is also possible that it be connected to another circuit not shown here.

Figure 12a shows the circuit diagram of a connection of a resonator stack in the serial branch and another resonator stack in the parallel branch between ports P1 and P2. The first resonator stack includes two resonators SR1 and SR2 connected in series. The second resonator stack includes two resonators PR1 and PR2 connected in series. An exemplary realization of this circuit is shown in schematic cross-section in Figure 12b. The first resonator stack is constructed as shown in Figure 10b. The second resonator

stack includes, from bottom to top, an electrode E6 (connected to ground, for example), a piezoelectric layer PS3, a center electrode E5, which is electrically connected with electrode E2 of the first resonator stack, a piezoelectric layer PS4 and an electrode E7 (connected to ground, for example).

Though not specifically shown in the figure, the (lower) resonators are, in this case, also arranged on a carrier substrate, an air gap or an acoustic mirror being provided, in each case, between the carrier substrate and resonator.

In the interest of clarity, only a few embodiments are described; however, the claims are not limited to these. Other variations are possible, especially in light of the possible combinations of the basic elements and arrangements presented above, as well as the number of layers in said layer regions of the resonator. The claims are not limited to a specific frequency range or a specific scope of application. Each of the layers of the resonator according (e.g., the piezoelectric layer or the electrode) can have a multilayer structure. The resonator can also contain a plurality (e.g., not adjacent to one another) of piezoelectric layers or more than only two electrodes.

The electrical connections (including the connections to ground) in the exemplary embodiments described can contain discrete elements, such as inductive resistors, capacitors, delay lines or adjustment networks.